PRECISE TIME DISSEMINATION AND APPLICATIONS DEVELOPMENT ON THE BONNEVILLE POWER ADMINISTRATION SYSTEM

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Abstract

The Bonneville Power Administration (BPA) uses IRIG-B transmitted over microwave as its primary system time dissemination. Problems with accuracy and reliability have led to ongoing research into better methods. BPA has also developed and deployed a unique fault locator which uses precise clocks synchronized by a pulse over microwave. It automatically transmits the data to a central computer for analysis. A proposed system could combine fault location timing and time dissemination into a Global Position System (GPS) timing receiver and close the verification loop through a master station at the Dittmer Control Center. Such a system would have many advantages, including lower cost, higher reliability and wider industry support. Test results indicate GPS has sufficient accuracy and reliability for this and other current timing requirements including synchronous phase angle measurements. A phasor measurement system which provides phase angle has recently been tested with excellent results. Phase angle is a key parameter in power system control applications including dynamic braking, DC modulation, remedial action schemes, and system state estimation. Further research is required to determine the applications which can most effectively use real-time phase angle measurements and the best method to apply them.

Introduction

Electric power systems have evolved from a few generators connected to a load in a nearby city to vast interconnected networks with hundreds of generators and loads spanning half the country. Commensurately time synchronization has evolved from locally set ac clocks with second accuracy to microwave pulse and satellite signals with microsecond accuracy. Modern power systems require increasingly complex controls to maintain stability. Recent developments in time dissemination provide an opportunity for major advancements in power system control, protection, and operation. Precise time distributed over a large power system allows synchronous sampling of voltage and current for real-time power and phase measurements as well as accurate event recording and fault location. Precise time and phase angle will enhance the development of regional real-time control systems.

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Time Dissemination

Early power system controls were based on power, current, and voltage measured at a terminal. Scheduling was handled by demand, and disturbances were localized enough that time synchronization was not required for analysis. As systems grew they became more complex and interconnected. Timing was required to coordinate scheduling and to compare disturbance recordings made across the system. Locally set ac clocks were adequate for the task in most cases, but created problems where distant clocks had been set several seconds apart.

In 1974, Bonneville Power Administration (BPA) commissioned the Dittmer Control Center in Vancouver, Washington, as the main dispatching and control center for the BPA system. A primary feature of the control center was the SCADA computer system to allow most of the system monitoring, switching, and control functions to be operated remotely. The Central Time System (CTS) synchronized to WWVB was installed as BPA's primary time source. Over the next decade time dissemination was extended throughout the system using IRIG-B over dedicated microwave channels.

The IRIG-B signal synchronized time throughout the system to at least tenths of a second 99 percent of the time. However, it was found phase slips in multiplex equipment and channel frequency response could cause enough distortion to make IRIG-B difficult to read, and noise could cause momentary interruptions. When recorded directly on an oscillograph, these impairments didn't cause much problem, but they played havoc with automatic decoding equipment. They caused time miscues that could be days off and take hours to resynchronize. In some locations automatic alarm recording equipment recorded pages of time errors. In addition, there were several BPA substations which didn't have direct microwave communications and needed accurate time.

GOES satellite receivers were installed at several sites in an attempt to solve both problems. Success was limited. They had trouble synchronizing, suffered from radio interference, and needed occasional antenna repointing. Time accuracy was no better than IRIG-B over the microwave although they did not need the millisecond delay corrections required for microwave transmission.

BPA has experimented with phase modulated IRIG-B and found it to be much more resistant to microwave impairments than the standard amplitude modulation. Since it is not available commercially and requires special encoding and decoding hardware, it has not been implemented. Consideration is being given to the whole spectrum of BPA's timing needs before developing a specialized system.

BPA is in the process of specifying a new CTS system for the Dittmer Control Center. GPS rather than WWVB will be used to acquire UTC time in order to achieve microsecond level synchronization. The system will employ triple redundant time generation for automatic switching and higher reliability. It will have an independent rubidium based clock for local verifiability and better local timekeeping in the event of GPS signal loss. The system will upgrade the central timekeeping capabilities to support all BPA system and Western region timing requirements for the foreseeable future.

Time Domain Fault Location

BPA has pioneered a unique system for locating power line faults (short circuits) using precise timing. When a fault occurs, the instantaneous change in potential creates a voltage wave that travels along the power line at nearly the speed of light. By precisely timing the arrival of the traveling waves at each end of a power line section, a simple formula yields the distance to fault from the end of the line **[1,2,3]**.

The original system, called Type B, had a master with a counter and several slaves that would relay the fault pulses to the master via microwave. The system was reasonably reliable, but could only be calibrated by known faults and needed to be interpolated by experienced personnel using information from past readings. The present version, called FLAR for Fault Location Acquisition Reporter, employs remote timetagging units with stable clocks at a number of substations [1]. The clocks are synchronized every 100 seconds by a phase shift keyed 2.3 MHz tone sent over the microwave. The remote units communicate over an automated data net with a master computer which retrieves these timetags, calculates the fault distances, and reports to system dispatching. This system has proven to be reliable and accurate for sites which can be linked by high frequency microwave communication. It is easy to use and is being improved with software to sort out good readings from the many generated by noise during a fault.

In 1989 the FLAR system was extended beyond the BPA microwave system by synchronizing the master with a GPS receiver. A GPS receiver installed at a substation can provide sync in place of the microwave transmitted pulse. The extension has worked well so far.

Requirements for a Combined System

The Western Systems Coordinating Council (WSCC) is a regional electric utility group which consists of 61 interconnected utilities west of the great plains from central British Columbia to Mexico. It has set a goal of 8 millisecond timing accuracy throughout the region. BPA has set its current requirement for 5 milliseconds maximum throughout its system, and 1 millisecond synchronization for all systems within a station.

Time domain fault location requires 1 microsecond synchronization throughout at least every area which might be reporting the same fault. Several other uses which have not been discussed yet are relaying, transient stability control, and state estimator. Relaying, which detects power line faults and controls the large power circuit breakers, optimally must be able to detect fault distance within 1000 meters to function correctly. Stability control and state estimation operate relative to the 60 Hz cycle which is 46 microseconds/electrical degree. These requirements are summarized in Table 1.

System Function	Measurement	Optimum Accuracy
Fault Locator	300 meters	1 microsecond
Relaying	1000 meters	3 microseconds
Transient Stability control	±1 degre	46 microseconds
State Estimator	±1 degree	46 microseconds
Oscillograph		1 millisecond
Event Recorder		1 millisecond

Table 1. Electrical Power System Precise Time Requirements

The most stringent accuracy requirement is fault location; any timing system with microsecond accuracy throughout the region will satisfy all the needs. Less obvious is the requirement for reliability and availability. Power systems are expected to operate all the time. Any control, protection, or monitoring system must be ready to operate reliably at any time. A timing system that operates reliably or produces the required accuracy 98 percent of the time is not acceptable. BPA currently

requires its control and communication systems to demonstrate a 99.986 percent availability for full performance operation. Any system with required outage times that cannot be scheduled into maintenance intervals (i.e., will fail occasionally at random times) is not acceptable. When systems fail the results can be dramatic–New York blackout of 1965–and destroy equipment worth millions of dollars.

IRIG-B sent over the microwave could achieve the 1 millisecond requirement using the phase modulation technique. Tests have demonstrated that it will never achieve 1 microsecond reliably, even with a steered oscillator. A Cesium oscillator at each station would achieve the required accuracy, but the necessary calibration and costs would be prohibitive.

GOES satellite receivers have proven to be not much better than IRIG-B sent over microwave. Radio signals such as WWVB do not give the required accuracy. Loran C is powerful in the Northwest and accurate but does not easily yield time.

The FLAR system has the accuracy and high reliability but only provides synchronization, not time of day. Incorporating time of day will require a major redesign of the hardware and software of the remote unit, an expensive and time consuming proposition. An additional shortcoming is its reliance on a direct high frequency microwave link which isn't available to all sites where BPA would like accurate time of day. It also is not available to neighboring utilities where synchronization may be desirable.

The GPS system can provide the 1 microsecond accuracy throughout the system. It is relatively new and has unproven reliability as far as BPA is concerned. However because it does offer such a great potential, BPA has purchased several receivers and has done extensive testing over the last 4 years. The advantages include good manufacturer support, less expensive, inherent delay compensation, no high frequency microwave requirement, better coordination with neighboring utilities, and an excellent system failure tolerance. The disadvantages are an imperfect receiver performance record to date, lack of knowledge of how the system will perform in a substation environment, and the uncertainty of Department of Defense policy. However recent results from GPS receiver testing have been excellent. That and policy statements by the Department of Defense have given enough confidence in the GPS system to propose a combined timing/fault locator system based on GPS.

Closed Loop Precise Time System

It has been proposed to install at each substation a GPS receiver with an IRIG-B output, a timetag option, and software that would allow it to communicate with the FLAR master. The receiver would provide precise time locally to the substation, timetag faults, and report times to the FLAR master. The master would additionally check the remote GPS time and operation. This system would eliminate the need for the high frequency microwave channel and several voice grade channels presently used to disseminate IRIG-B. It would replace the time code generator and FLAR remote unit with a single GPS receiver. Further advantages include:

a. **Manufacturer Support** The current FLAR system is BPA designed and supported. A proposed phase shift key modulated IRIG-B would also need to be designed for BPA. The proposed system would add only two options a basic GPS receiver produced by several manufacturers. The options are likely be used by many utilities, potentially making the configuration a standard piece of equipment.

b. **Less Expensive** At today's prices, the GPS receiver unit is competitive with the two remote units it would replace. With quantity production, and as GPS receiver technology improves, the cost would be less. Additional savings are realized by microwave capacity not used.

c. **Inherent Delay Compensation** The broadcast delay from the CTS to each substation has to be calculated and entered in each remote unit. BPA is in the process of implementing an alternate control center from which time code could alternately be broadcast, creating two different delays for each remote. Alternate path routing for catastrophic microwave system problems further complicate the problem. A GPS receiver outputs time corrected for its location.

d. **Closed Loop Verification** The present broadcast IRIG-B has no verification that the time is correct and the remote equipment is operating. FLAR is a closed loop system, reporting every 100 seconds any events and remote status. The proposed system would report GPS receiver health, oscillator status, and tracking information if required. It would also report local time to verify timekeeping within a millisecond. An additional timetag input can be added to receive broadcast FLAR sync pulses to verify timing to a microsecond. The master could also set the remote for daylight time changes and tracking schedules if needed. Verification of remote operation should remove much of the uncertainty of relying on a remote clock that receives its signals from tiny dots in space.

e. **Improved Inter-utility Synchronization** Even a precise central system can drift from a common reference (UTC); when it does, all nodes drift with it. If each substation is directly synchronized to the same source as all other utilities, the systems on the average will remain better synchronized at all times.

f. **Improved Systematic Reliability** While the centralized system broadcasts from a redundant CTS on a microwave system of very high reliability, there are common power sources, single wire interconnections, and combined signal paths. Any interruption of this long linked chain or error in time generation can cause multiple remote outages. GPS relies on multiple satellites, each individually timed with extensive built in redundancy. Incorrect control signals to the satellites could cause errors, but not likely with all satellites at once. Since several satellites are in view at all times, receivers can be designed with logic to ignore signals from a satellite with sudden changes or with excessive variance from the others in view. The GPS receiver itself uses an internal oscillator which is slaved and compared with the satellite signal. If the RF input fails for any reason, the internal time generation can carry the output accurately for some period of time. If the internal timekeeping generates an error, it can be corrected from the GPS signal. Communication failure interrupts fault reporting and verification, not time. Catastrophic failure of any station does not affect the timing at any other station.

A test program is planned to deploy several units with the required software and three timetag inputs, one for faults, one to mark the operation of the station oscillograph and the other to time the arrival of the sync pulse. The oscillograph will typically only trigger on significant disturbances, so the FLAR master uses its trigger to sort possible faults from the many timetags due to noise and switching. Timing the sync pulse will allow long term monitoring of performance to the highest accuracy level. The test program will allow BPA to develop a longer term performance and reliability record.

Precise Time and Phase Measurement R & D at BPA

GPS Receiver Testing

In conjunction with the Phasor R & D program, BPA has tested GPS receivers for use in timing on the BPA system. Since continuous accuracy is the main concern, testing has focused on long term monitoring of the output. In most GPS receivers a 1 Pulse Per Second (1 PPS) signal provides internal sync for all other timekeeping signals, so it provides a simple reference for monitoring overall performance. The 1 PPS output was compared against a 1 PPS signal generated locally by a Cesium reference standard. Originally only the average between the two sources was measured and computed periodically. It was found that unlike an oscillator, the GPS derived signal could make sudden jumps to another value for one to many seconds and then snap back. Testing was expanded to monitor the 1 PPS signal every second for jumps as well as take 100 second averages every 15 minutes. A 100 second average provides reasonable noise smoothing that fits in well with the 15 minute interval, though it may not provide the best sigma tau variance.

In the last 6 years we have seen receivers improve from units that kept time within several microseconds only 95 percent of the time to units that typically keep tenths of microsecond accuracy 99.9 percent of the time with less than 3 microsecond deviation at any time. The improvement is partly due to better satellite coverage but mostly due to receiver technology development. Performance at the present level is quite acceptable to BPA. Figure 1 is a 2 week plot of the 100 second averages comparing GPS with Cesium. The drift of 1.6E-12 of the Cesium standard relative to UTC is left in the plot so the curves for each week don't overlap.

We have also compared a GPS receiver installed at the Malin Substation with the FLAR sync pulse received at that site. Malin is in southern Oregon on the California border and about 260 air miles from the Dittmer Control Center. The sync pulse delay time was measured by transmitting the signal from Dittmer, re-transmitting it back, and measuring the round trip time. An average of 400 measurements was divided by two to estimate a one way transit time of 1689.3 microseconds. Since the FLAR master at Dittmer is now synchronized by GPS, it is easy test the one way transit time with a GPS receiver at Malin. The transit time averaged over 15 minute intervals is around 1691.3 microseconds, very close to the previously calculated time (Figure 2). The 2 microsecond difference was constant over the 5 month monitoring interval and has not been investigated, but is probably due to additional cable and transmitter equipment at Dittmer and differences in microwave system filter tuning. The effects of the microwave system and GPS receivers cannot be separated in this data, but even combined they are within an acceptable performance level for the FLAR system.

While the averaged data only varied around 300 nanoseconds from the mean, of greater concern is the worst case performance. Figure 3 is a plot of the span between the maximum and minimum measured during the interval. The time interval counter used in this test only has a 100 nanosecond resolution so the plots appear rather quantized. The fact the difference is always less than 1.5 microseconds is amazing, considering the plot combines the effects of two GPS receivers 260 miles apart and the microwave communications in between.

Synchronous Phase Angle Measurements R & D Program

BPA installed a prototype Synchronous Phasor Measurement System developed by the Department of Electrical Engineering at Virginia Polytechnic Institute and State University in Blacksburg, Virginia on BPA's 500 kVAC Pacific Northwest-Southwest (PNW-SW) Intertie. The system consists of a remote terminal installed at John Day and Malin Substations (about 250 miles apart) and a master terminal

at the BPA Laboratories in Vancouver, Washington. The two remote terminals are synchronized by GPS receivers.

A remote unit is a microcomputer with a A/D and serial interfaces. Three phase power line waveforms are synchronously digitized at a 720 sample/second rate, clocked directly by a precisely timed signal from the GPS receiver. After each sample, the latest 12 samples are filtered with a Fourier transform to extract the 60 Hz component and converted with the symmetrical component transformation to yield the complex positive sequence phasor. This phasor represents the magnitude and phase of a balanced three phase system and is a good representation of the state of a real power system in all but extreme fault conditions. Since each phasor is computed with 12 samples, it gives a true 60 Hz response to changes. The precise timing makes data comparable for accurate phase angle determination over a region of any size [**7,8**].

In addition to calculating phasors, the remote also computes frequency and rate of change of frequency. It monitors the computed data for sudden changes and flags any that go beyond preset limits. It will communicate these values to the master terminal on demand either as a stored table or a real time data flow.

In this test, data was gathered from the real time data flow using 4800 BPS modems over the BPA microwave system. Data was transmitted at 12 Hz (every 60th sample) in order to fit into the protocol and data rate. The master monitored the disturbance flags and saved a 3 minute table of raw data (including 30 seconds of preflag data) whenever a flag was detected. The master also computed continuous statistics from the data and recorded it every 15 minutes. The test system diagram is shown in Figure 4.

Phasor System Test Results

The purpose of the test program was both to evaluate the phasor measurement system and to provide operational information on the GPS receivers used for the precise time source. The system has been fully operational since September, 1990, and 8 months of continuous data has been recorded for analysis.

The system has performed very well. In 2 years of field of deployment there has only been one hard failure in a GPS receiver and none in the phasor remote units. Data communications has less than a 1 percent error rate. The phasor data appears to have a better response with greater accuracy and less noise than comparable analog telemetered data. The final test results are now being analyzed with a report to follow in 1992.

A sample disturbance records a bus fault at the WNP-2 plant near Richland, Washington, followed by a loss of 1094 MW of generation at 10:10:55 on December 7, 1990. A sharp voltage dip is seen at both John Day and Malin during the fault (about 30 milliseconds duration). It is followed by a voltage rise and decrease in phase angle between John Day and Malin which accompanies the drop in power transfer. The frequency traces from the two stations are nearly identical; the squared appearance is due to the algorithm being used at the time which takes longer averages to improve accuracy near 60 Hz. The system gradually approaches its old operating point during the 2 minutes following the fault.

Future Applications of Precise Time and Phase Angle Measurements

Precise timing enables implementation of event time-tagging, fault location, and the synchronous measurements of key transient stability indicators such as voltage phase angle in near real time. These measurement techniques enable the development of new protection and control schemes, some of which are described in the following paragraphs.

Stability Control Schemes

The aim of stability control schemes is to prevent unnecessary shutdown of generators, loss of load, separation of the power grid, and avoid blackouts and damage to power system equipment. Control schemes accomplish this by a graduated response to system disturbances which only take effect when the disturbance is significant enough to endanger overall system stability. When a disturbance is great enough to cause generators to go out-of-step, the frequency to become unstable, or the voltage to collapse, controls respond with appropriate remedial measures such as dynamic braking, generator dropping, load shedding, and finally controlled islanding.

Existing control schemes within the WSCC service area are Type A high speed actions based on a worst case scenario and Type B which takes slower corrective action after an event. Type A controls tend to take excessive action and can only respond to preprogrammed events. Type B tend to be too little or too late to prevent system problems to propagate as they would with no control action.

Future stability control systems based on digital phase measurement can offer significant advantages over the systems currently employed. Phase measurements could be combined with Type A high-speed control logic to compute an appropriate proportional response and be substituted for Type B for longer term control actions. During a major system disturbance, control computers can sort and process synchronous field data to compute a response appropriate to the current system operating conditions. Within a few cycles from the beginning of the disturbance, they can provide an output response to the disturbance. If this initial high-speed action doesn't stabilize the system, further Type B actions could be taken to taken to correct it. Considerable long range R & D is required to assess the feasibility of such systems and develop and verify the necessary strategies, hardware, and software.

HVDC Modulation

HVDC systems are powerful tools for improving the transient and dynamic stability of AC power systems. In contrast to an AC line, the power transfer over a DC link does not depend on the voltage phase-angle between the ends of the line and can be quickly changed independently from other system parameters. The control may be continuous in nature, using feedback variables, or it may be discrete, consisting of predetermined changes in DC power. Voltage phase angle between stations in the AC system are powerful input parameters for this type of control. The first swing (transient) stability can be improved by using a voltage phase angle measurement on an AC line to modulate the parallel HVDC link. Damping of oscillations in the AC grid can also be achieved by using the rate of change of voltage phase angle as an input to the DC Link control.

Dynamic Braking

When a power line fault occurs, the current is shorted back to the generator bypassing the load. Since power system equipment is mostly inductive rather than resistive, it absorbs little energy, so the driving force tends to accelerate the generators. In North-central Washington BPA has a 1400 MW resistor which serves as a dynamic brake for the many large hydro generators in the area. It is used to prevent AC system separation by burning up excess kinetic energy from system generators. At present, the beginning of braking is usually triggered by the detection of a disturbance such as a multi-phase fault or intertie separation. The brake is applied once for 30 cycles to stabilize the initial swing. A single application may be too little or too much to stabilize the system for a particular incident. Voltage phase angle could integrated into a dynamic control that could apply the brake to maintain phase within a maximum limit using up to six, consecutive 30 cycle applications.

Subsynchronous Resonance

In a multi-machine power system the controls on the various generators will at certain operating points with certain power grid configurations oscillate at a low frequency and amplitude, threatening operating stability and putting undue stress on generation equipment. This subsynchronous resonance is a well known and generally controlled phenomena, but hard to eliminate entirely due to many possible operating configurations in a large power grid. The ability to measure voltage phase angle between key generating units would provide a means of avoiding or damping out some of these oscillations.

System State Estimation

System State Estimation is a mathematical technique that has evolved for determining stability of a power system based on its characteristic equations. The major input requirement is knowledge of the complex voltages at the power system busses throughout the system [8].

The present State Estimator uses a least squares algorithm to compute the complex voltages from raw power system data like voltage magnitudes and power flows. Thus the voltage phase-angles are derived in the estimation process rather than obtained by direct field measurement. The slow response time (seconds to minutes) renders the system usable only for static analysis. In addition, it requires consistent and complete sets of measurements to accurately implement the algorithm. When the data is inconsistent or missing, system phase angles are abnormally large, or the system is in an oscillatory condition the solutions may not converge. Line flow measurements are needed for any bus to be included, so the contribution of neighboring power systems may be impossible to compute even though they contribute to system stability.

A State Estimator that uses direct phase angle information measured by precise time synchronous sampling would avoid most of these problems. The system would be fast (in the order of a few cycles) since the complex voltages used in the algorithm would be measured rather than computed. If a reading was in error or missing only estimations surrounding a particular bus would be thrown out. Abnormal phase angles and system oscillations would not affect the process. State estimation could be incorporated into dynamic control schemes.

Monitoring Power Flow.

The power flow across a line is equal to the product of the two terminal voltages and the sine of the phase angle across the line divided by the line impedance [4]. The terminal voltages are normally

closely regulated to a fixed value and the transmission line is usually constant. Thus, the power flow is basically determined by the voltage phase-angle difference between the busses. A maximum phase angle can be determined based on the line and bus-generator characteristics, above which the generators will not stay in sync. This stability limit then determines the maximum power that can be transmitted across the power line.

Monitoring voltage phase angles rather than line loading for power system security assessment may be a more reliable method. Generally speaking, in multi-machine systems small angles between the regions or buses is "relatively secure" and angles approaching 90 degrees is unstable. If bus voltage phase angles along with stability margins were displayed for system dispatchers on the power system diagrams, the load flow and stability situation could be verified at a glance.

Monitoring Reactive Power Requirements

The reactive power injections which are required for controlling voltage magnitudes in the power system depend basically on two factors: the load characteristics and the reactive losses in the network. Phase-angles are important quantities in this respect because they influence the reactive losses in transmission lines, especially for large angles.

This relationship was a major factor in the voltage collapse and subsequent blackout in France in 1978 and the blackout in the SW region of California in 1982. Abnormally large angles produced large power transfers. These, in turn, increased the demand for large reactive compensation and the system became unstable when it was not available.

High speed phase measurements will allow real-time monitoring of the reactive power requirements of the of the system or a region. Following a system disturbance it is fast enough to initiate high-speed reactive compensation, such as shunt capacitor switching to control voltage.

Reduction of Losses

From precise synchronous field data it is possible to construct a precise computer model of the system. By using this model, computer studies could be run to match a specific load demand at minimum losses. Security considerations permitting, savings could be realized for example, by opening some lines which carry essentially no load at a specific time of the day or season.

System Restoration

Following a major blackout, generating plants or regions can be reclosed rapidly if they are in phase with one another. With remote voltage phase-angle measurements at key points, it would be possible to synchronize and restore remote substations reliably and securely. This should make system restoration faster and more versatile.

Summary

BPA is continuing research on precise timing systems and applications development for operation and control of its electric power system. It has developed and employed an accurate and reliable fault locator system and the precise timing network that enables it to operate. GPS is being used to extend the range of that system beyond BPA's network. Investigation also continues of better

methods to dissemination system time. A demonstration R & D project is being initiated to combine time dissemination and fault location timing into a GPS receiver.

Research in system wide phase angle measurements is also continuing. The first test phase of a phasor measurement system has been completed. A GPS receiver provides the precise timing required for the synchronous sampling used to compute voltage and current phasors. Results have been very good, and consequently new system deployment is being investigated.

A successful phase angle measurement system will have many applications. These include a new generation of controls including remedial action schemes, dynamic brake and capacitor insertion, DC system modulation, and system state estimation. As power system loading and interconnection increase, new and more automated controls will need to be developed. High speed, real-time phase angle measurement may prove to be a key to the next generation of controls.

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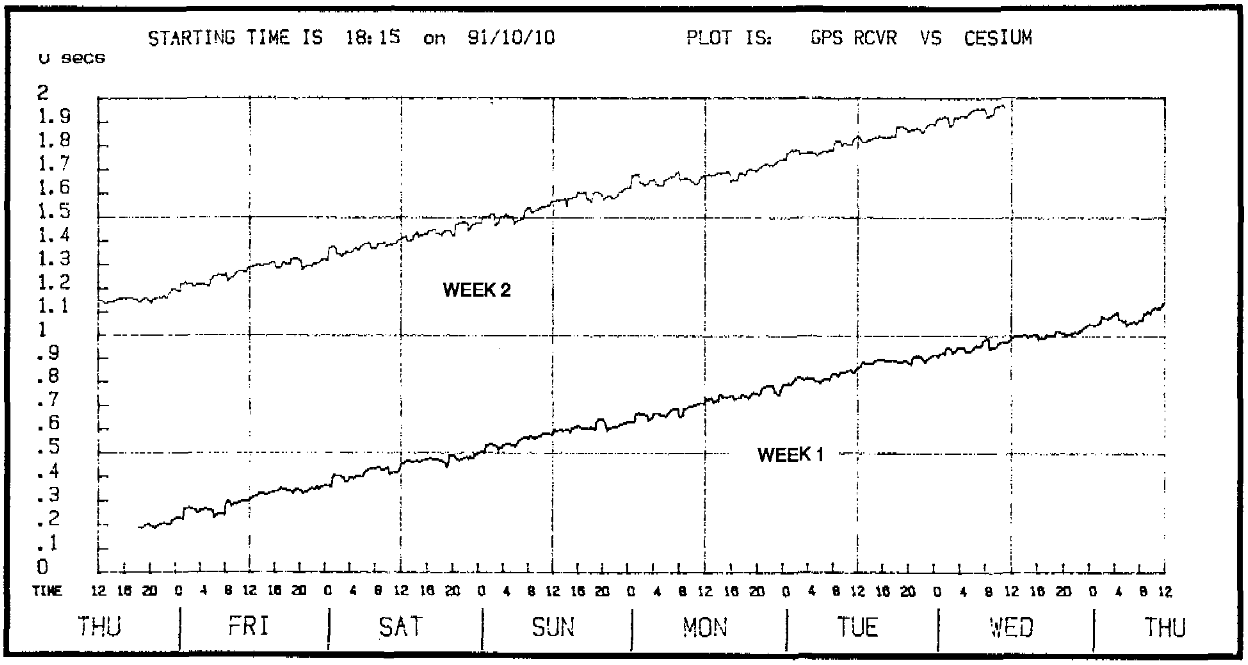

Figure 1. Typical GPS receiver performance versus a Cesium Standard.

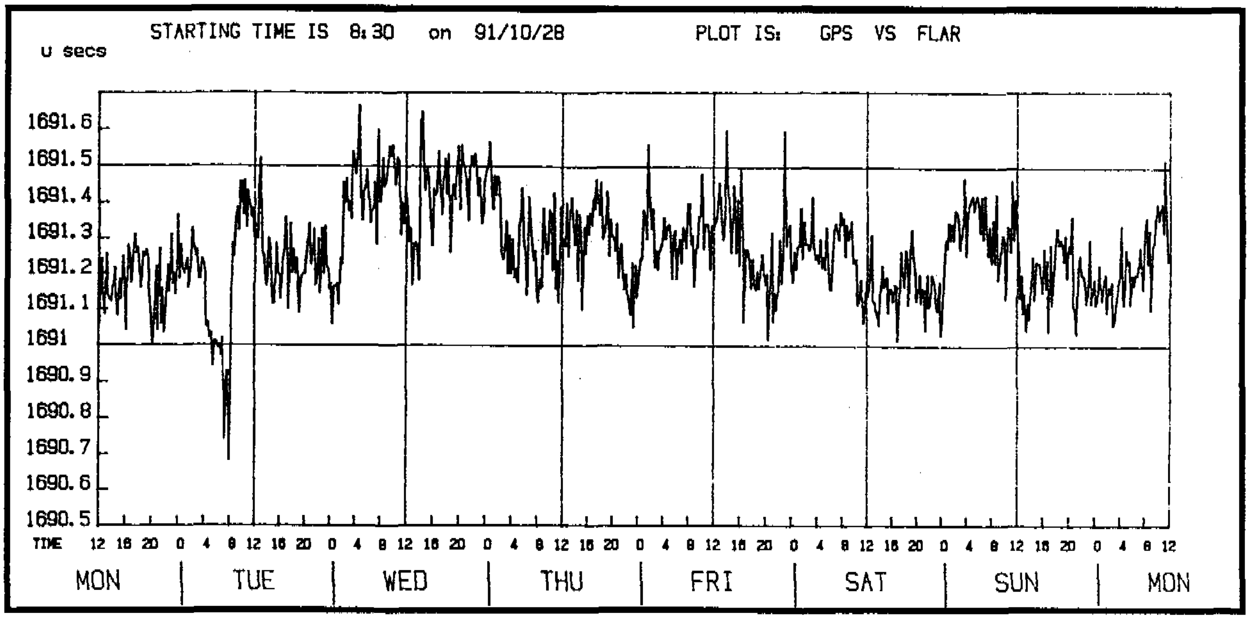

Figure 2. Average of FLAR versus GPS timing.

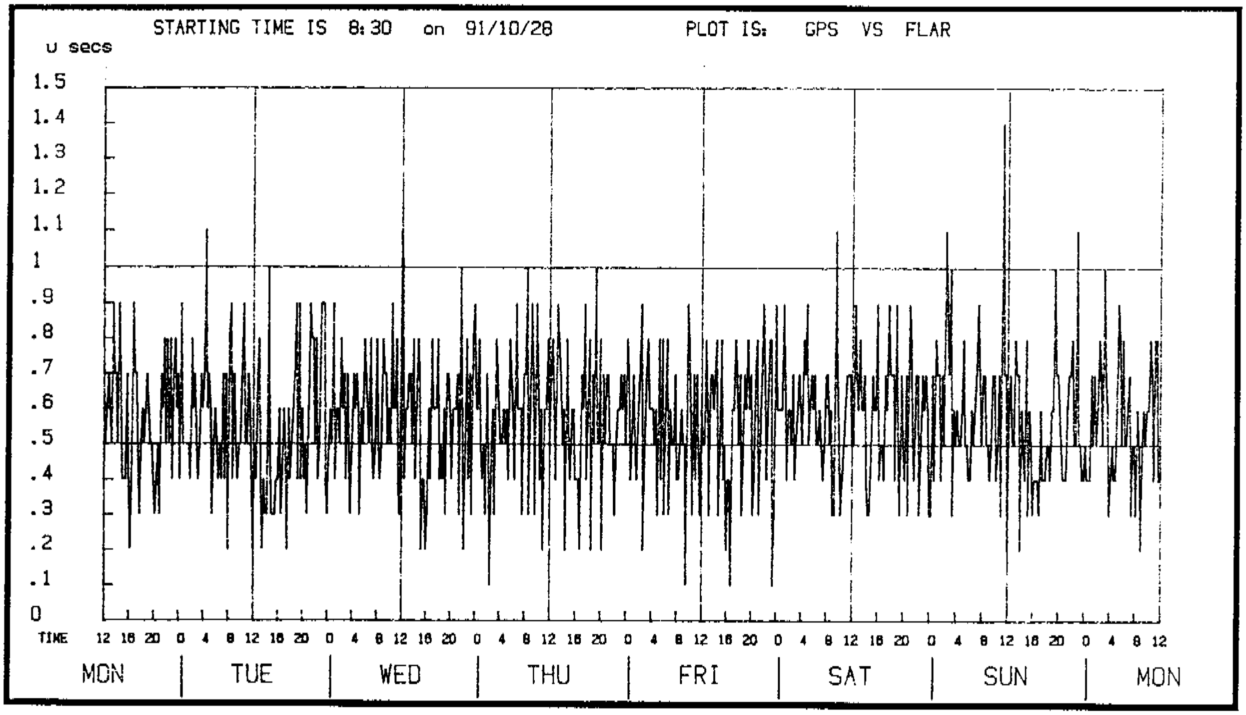

Figure 3. Worst Case of FLAR versus GPS timing (Span or Maximum-Minimum).

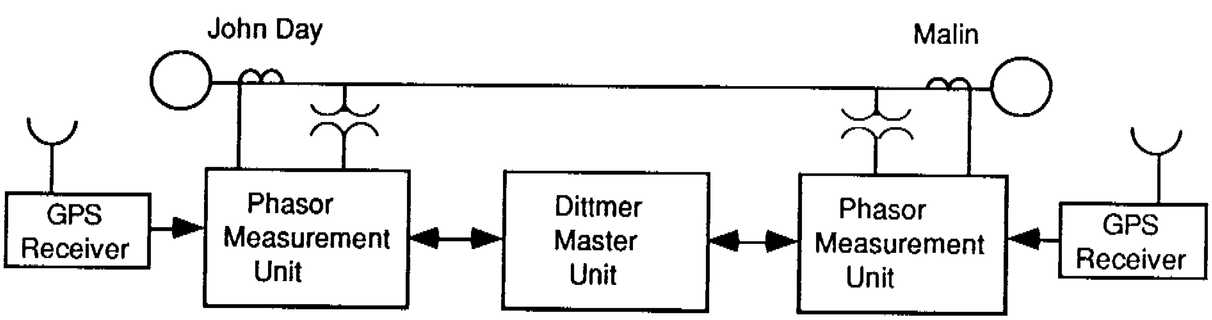

Figure 4. Synchronous Phasor Measurement System One line Diagram

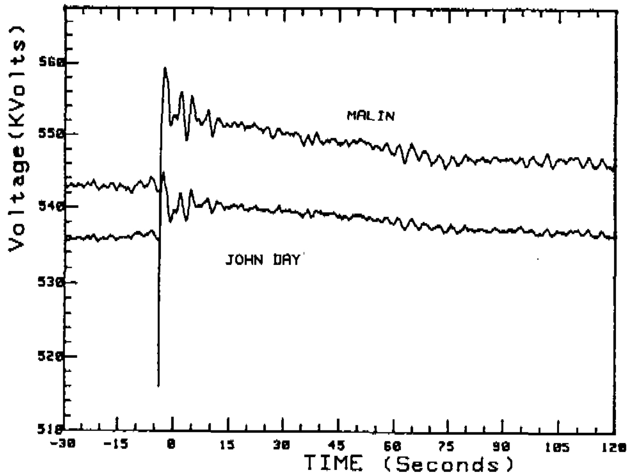

Figure 5. Voltage Magnitude at John Day and Malin Substations

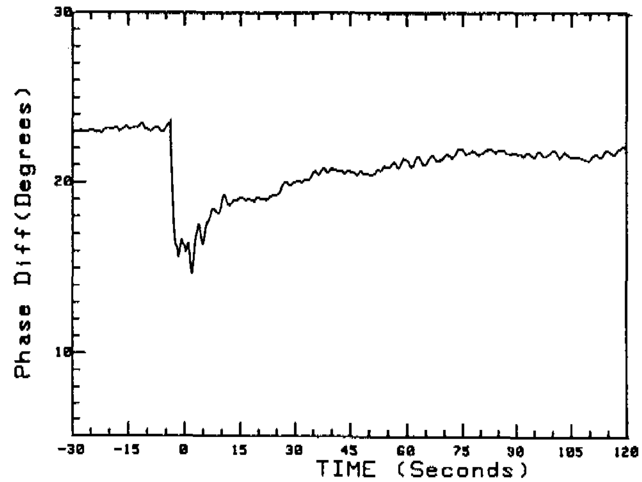

Figure 6. Voltage Phase-Angle between John Day and Malin Substations

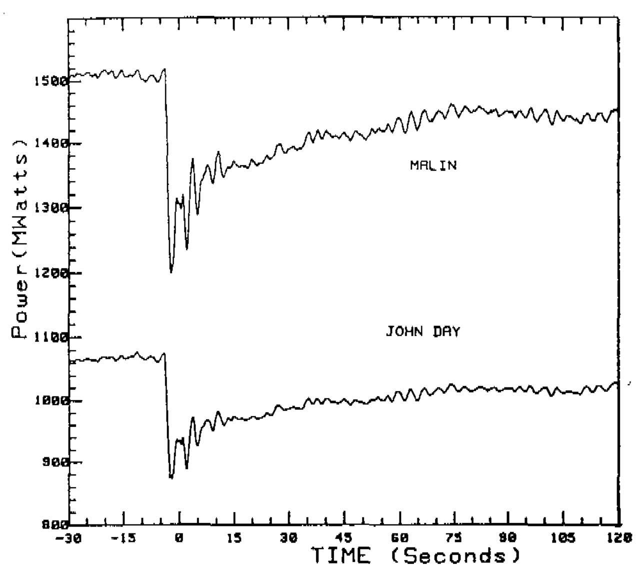

Figure 7. MW Power flow on Line 1 at John Day and Malin Substations

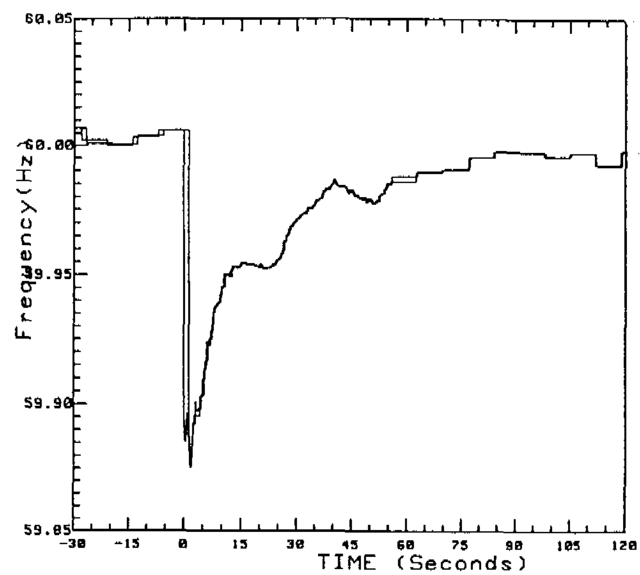

Figure 8. Frequency at John Day and Malin Substations